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Looking back in time beyond the big bang

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Abstract

String theory can (in principle) describe gravity at all curvature scales, and can be applied to cosmology to look back in time beyond the Planck epoch. The duality symmetries of string theory suggest a cosmological picture in which the imprint of a primordial, pre-big bang phase could still be accessible to present observations. The predictive power of such a scenario relies, however, on our ability to connect in a smooth way the pre-big bang to the present cosmological regime. Classical radiation back reaction seems to play a key role to this purpose, by isotropizing and turning into a final expansion any state of anisotropic contraction possibly emerging from the pre-big bang at the string scale.

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The standard cosmological model is, rightfully, one of the most celebrated scientific conquests of the present century. Such a model, however, cannot be extrapolated back in time beyond an initial regime approaching a state of infinite density and curvature – the so-called "big bang". The history of the Universe from the big bang down to the present time is more or less well known, and its various aspects are under active study since more than forty years [1]. But what happened before the big bang?

This question has not been raised until very recently, mainly because of the lack of a systematic application to cosmology of the powerful instruments of modern theoretical physics, able (in principle) to look back in time beyond the Planck scale. As a consequence, the big bang has represented so far a sort of "Hercule's Pillars " of cosmology. In the ancient times, when nobody knew the world beyond the Straits of Gibraltar, because nobody sailed the sea beyond that point, it was common opinion that Gibraltar would represent the end of the world itself. In the same way, today, the big bang is often popularly referred as the beginning of the Universe, the beginning of spacetime, the beginning of "Everything", just in view of the lack of information about earlier time scales. There are also respectable scientific attempt, in a quantum cosmology context, to explain the origin of the Universe and of the spacetime itself as a process of tunnelling "from nothing", i.e. from some unspecified vacuum [2]. They are affected, however, by problems of boundary conditions [3], arising just because of the ignorance, intrinsic to standard cosmology, about the state of the Universe before it emerged at the Planck scale.

The standard cosmological scenario has been complemented and improved, in many aspects, by the inflationary scenario [4]. Concerning however the very beginning of the Universe, i.e. the state and the evolution of the Universe before the Planck epoch, the situation in conventional inflation is not so much different from that of the standard model, because a phase of conventional inflationary expansion, at constant curvature, cannot be extended back in time for ever [5]. Quoting Alan Guth's recent survey of inflationary cosmology [6]:

"... Nevertheless, since inflation appears to be eternal only into the future, but not to the past, an important question remains open. How did all start? Although eternal inflation pushes this question far into the past, and well beyond the range of observational tests, the question does not disappear."

String theory seems to suggest an answer to this question and, most important, seems to suggest that the beginning of the Universe, namely its evolution at times earlier than

Planckian, might be not completely beyond the range of present observational tests, in contrast to the sentence quoted above. The technical instrument used by string theory to look back in time, beyond the Planck scale and the big bang singularity, is (a general version of) the duality symmetry which, together with supersymmetry, is probably one of the most powerful and important tools of modern theoretical physics (at least, because they are both at the grounds of superstring theory [7], which is at present one of the best candidate for a Theory of Everything).

Just like supersymmetry associates to any bosonic state a fermionic partner, and vice-versa, duality associates to any cosmological configuration with decreasing curvature a geometric partner with growing curvature, and vice-versa. Just like supersymmetry cancellations can eliminate the field theory divergences, duality symmetries are expected to regularize the spacetime and curvature singularities. The assumption of (at least approximate) "self-duality" symmetry, which combines duality and time reversal, suggests in particular a complete model of cosmological evolution, defined in cosmic time from minus to plus infinity, in which the Universe expands around a fixed point of maximal (finite) curvature, controlled by the fundamental length scale L_s of string theory [8].

The big bang singularity is replaced in this context by a phase of high (nearly Planckian) curvature, which marks the transition from an initial accelerated growth of the curvature H and of the string coupling g_s (parametrized by the dilaton ϕ as $g_s = e^{\phi/2}$), to a final state of radiation-dominated, decelerated expansion at constant dilaton. It comes natural, in this context, to call "pre-big bang" the initial phase of growing curvature, in contrast to the subsequent, standard "post-big bang" evolution, with decreasing curvature.

The most revolutionary aspect of this scenario is probably the fact that the high-curvature, Planckian regime is reached *at the end*, and not *at the beginning* of inflation. Thus, the state of the Universe at the Planck scale does not represent an initial condition, but is rather the result of a long and classical pre-big bang (i.e. pre-Planckian) evolution, which starts from a state of very low curvature and small coupling ($H \ll L_s^{-1}$, $g_s \ll 1$), and is well controlled by the low-energy string effective action. In other words, the Universe is far from being a "new-born baby" at the time of the big bang transition, being instead almost in the middle of a very long, possibly infinite, life.

From a phenomenological point of view, the important aspect of this scenario is the fact that the cosmological evolution preceding the Planck epoch may become accessible to present

(direct or indirect) observations. I would like to recall, in particular, three possible effects, referring to observations to be performed *i)* in a not so far future, *ii)* in a near future, and *iii)* to observations already (in part) performed. They are, respectively: the presence of a graviton background much stronger than expected in standard inflation [9], the contribution of massless (or massive) axion fluctuations to the CMB anisotropy spectrum [10], and the production of primordial "seeds" for the cosmic magnetic fields [11].

The predictive power of this scenario relies however on the construction of non-singular models, describing a smooth transition from the pre- to the post-big bang regime. Implementing such a transition is in general problematic in the context of the tree-level, gravi-dilaton string effective action; there are "no-go theorems" [12] excluding a regular transition also in the presence of perfect fluid and axionic Kalb-Ramond sources, and suggesting the need for higher order (quantum loops [13] and higher curvature [14]) corrections. Examples of a complete transition through the strong coupling regime have been implemented, up to date, but only with the help of "ad hoc" corrections: a non-local two-loop [15] or four-loop [16] dilaton potential, a higher derivative dilaton kinetic term [17].

The above non-go theorems are all formulated in the context of homogeneous and isotropic backgrounds. It is known, on the other hand, that the singularity can be "boosted away" already at the tree-level [18] (through an appropriate transformation of the global, pseudo-orthogonal duality symmetry group), provided the metric is allowed to be anisotropic. There are examples [18], dating back to the early studies of the pre-big bang scenario, of anisotropic solutions with a non-trivial axion background which satisfy all the conditions [17] necessary for a "graceful exit" from the pre-big bang phase, and which describe indeed a perfectly smooth transition from an initial growing curvature and dilaton phase, to a final decreasing curvature and dilaton phase.

Such examples are usually regarded as unrealistic, mainly because in the final post-big bang regime the metric background may be contracting; if expanding, it is nevertheless highly anisotropic, with only two dynamical (spatial) dimensions (the background is frozen in all the other space directions).

It should be taken into account, however, that the background transition described by the above solutions generates a large amount of radiation: the quantum fluctuations of the initial pre-big bang state are amplified by the accelerated evolution of the background, and re-enter the horizon in the subsequent decelerated phase, contributing eventually to the

post-big bang sources as a gas of relativistic particles. In the post-big bang phase, this radiation tends to become dominant with respect to the axion sources [19], and it is well known that the radiation can isotropize an initially anisotropic metric [20]. In a contracting background, we may expect that the radiation energy density become dominant even faster, and may even turn the initial contraction into a final expansion, as suggested by the general radiation-dominated solution of the gravi-dilaton cosmological equations [21].

To confirm this expectation, I will now present the results of a numerical computation which shows the changes induced by the radiation back reaction in the final state of the regular solutions [18]. The aim is twofold: *1)* to stress the possibility of a smooth connection between the pre-big bang Universe and the present isotropic, expanding Universe also to lowest order in the string effective action, without any "ad hoc" higher order correction (the importance of the low energy string effective action has been recently stressed also in the context of M-theory [22]); *2)* to point out the possible relevance of contracting backgrounds for the solution of the graceful exit problem of string cosmology.

I will concentrate on the particular class of regular backgrounds obtained by boosting the dual of the two-dimensional vacuum Milne solution. The dilaton, the non-vanishing components of the metric and of the antisymmetric axion field, $B_{\mu\nu} = -B_{\nu\mu}$, can be written in the synchronous gauge as follows [18]:

$$\begin{aligned}
&\phi = \phi_0 - \ln\left(\beta + \alpha b^2 t^2\right), \quad g_{11} = -\frac{\alpha + \beta b^2 t^2}{\beta + \alpha b^2 t^2}, \quad g_{12} = -\frac{\sqrt{\alpha\beta}\,(1 + b^2 t^2)}{\beta + \alpha b^2 t^2}, \\
&g_{00} = -g_{22} = -g_{33} = 1, \quad B_{12} = g_{12}, \quad \alpha = \cosh\gamma + 1, \quad \beta = \cosh\gamma - 1,
\end{aligned} \tag{1}$$

where ϕ_0, b and γ are real arbitrary parameters. This background represents an exact anisotropic solution of the tree-level string cosmology equations:

$$\begin{aligned}
&R_\mu{}^\nu + \nabla_\mu\nabla^\nu\phi - \frac{1}{4}H_{\mu\alpha\beta}H^{\nu\alpha\beta} = 0, \qquad R - (\nabla_\mu\phi)^2 + 2\nabla_\mu\nabla^\mu\phi - \frac{1}{12}H_{\mu\nu\alpha}H^{\mu\nu\alpha} = 0, \\
&\partial_\nu\left(\sqrt{|g|}e^{-\phi}H^{\nu\alpha\beta}\right) = 0, \qquad\qquad H_{\nu\alpha\beta} = 3!\partial_{[\nu}B_{\alpha\beta]}.
\end{aligned} \tag{2}$$

The time evolution of the dilaton and of H_1, which represents the rate-of-change of the distance along the x_1 direction between two comoving geodesics, is illustrated in Fig. 1. The parameter H_1, which is the analog of the Hubble parameter for anisotropic, off-diagonal metrics, is defined by $H_1 = \theta_{\mu\nu}n^\mu n^\nu$, where n^μ is a unit space-like vector along x_1, and, in the synchronous frame, $\theta_{\mu\nu} = \nabla_{(\mu}u_{\nu)}$ is the so-called expansion tensor for a congruence of

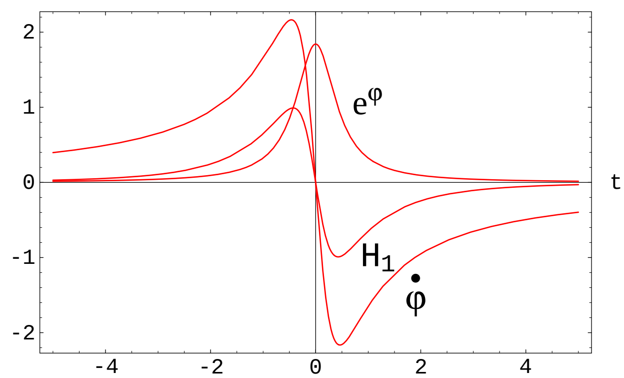

FIG. 1. *Smooth evolution from an expanding pre-big bang configuration to a contracting post-big bang configuration, according to the solution (1), with* $\phi_0 = 0$*, and* $b = \gamma = 1$.

co-moving geodesics u^μ [23]. As clearly shown in Fig. 1, the initial accelerated expansion ($H_1 > 0, \dot{H}_1 > 0$), evolves smoothly into a final decelerated contraction ($H_1 < 0, \dot{H}_1 > 0$). The evolution is non-trivial only in the $\{x_1, x_2\}$ plane, as $H_2 = H_3 = 0$. Notice that, with an appropriate choice of the parameters, it is always possible to bound the peak values to be smaller than one in string units, consistently with the low-energy effective action.

In the above background, the transition to the post-big bang regime amplifies the quantum fluctuations of the initial pre-big bang state. In other words, the final post-big bang state is characterized by a large number of massless particles (gravitons, dilatons, photons...), produced in pairs from the vacuum [19]: their total energy density ρ is bounded by the maximal curvature scale of the background, which, in its turn, is controlled by the string length scale L_s. Their effective averaged stress tensor is traceless [24], and we can thus represent their contribution to the post-big bang background like that of an effective radiation fluid, with $\langle\rho\rangle = \langle 3p\rangle$ and $\langle\rho\rangle \lesssim L_s^{-4}$. This contribution is weighed by the dilaton, in the string frame [8], as $\langle\rho\rangle e^\phi$, and it is initially subdominant at the beginning of the post-big bang phase, but tends to grow in time with respect to the axion.

To take into account this back reaction, I have added to the right hand side of the first of equations (2) the contribution of the effective radiation stress tensor, $e^\phi\langle T_\mu{}^\nu\rangle$ (in units $8\pi G = 1$), and I have numerically integrated the system of equations (2) plus the conservation equation $\nabla_\nu\langle T_\mu{}^\nu\rangle = 0$ (which is still valid in the usual form, in spite of the dilaton [8]). I have imposed the boundary conditions that the background starts initially (at

large and negative times) in the configuration described by the solution (1), and that the radiation keeps negligible until the background is well inside the post-big bang regime. The evolution is thus unchanged in the pre-big bang phase, but the final stage of the post-big bang evolution is qualitatively affected by the radiation back reaction, as illustrated in the three following figures where the results of the numerical integration (plotted as solid curves, with time measured in units of b^{-1}) are compared to the unperturbed solution.

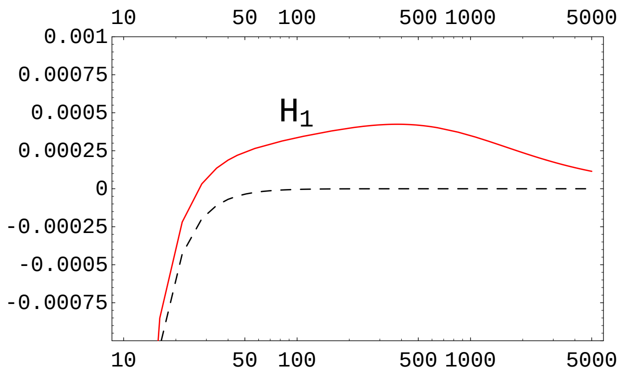

FIG. 2. *Time evolution of H_1. With the inclusion of the radiation back reaction (solid curve) the decelerated contraction of Fig. 1 (dashed curve) becomes decelerated expansion, with H_1 positive and asymptotically decreasing.*

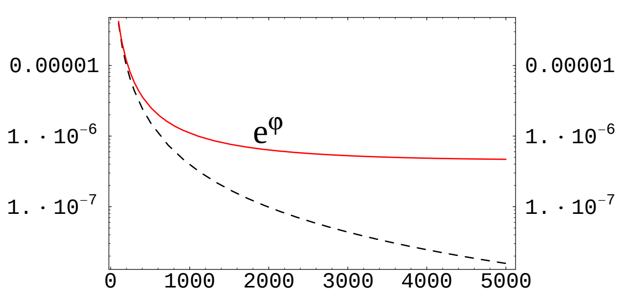

FIG. 3. *Time evolution of the dilaton. The friction of the radiation back reaction tends to stop the dilaton (solid curve), with respect to the axion-dominated solution of Fig. 1 (dashed curve).*

There are three main effects: the contraction turns eventually into a standard decelerated

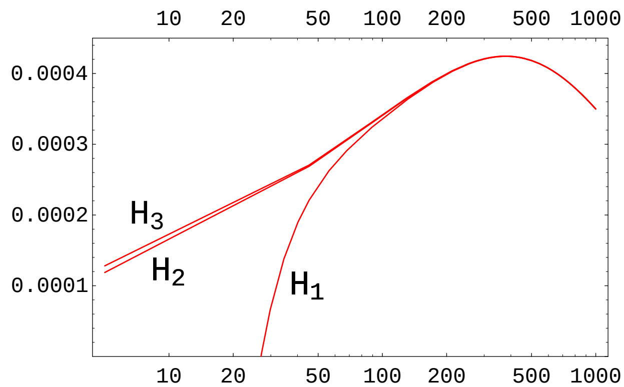

FIG. 4. *Time evolution of H_1, H_2, H_3, with the inclusion of the radiation back reaction. All the spatial dimensions become dynamical, and the background converges to a state with the same rate of decelerated expansion along any direction.*

expansion, with $H_1 > 0$ and $\dot{H}_1 < 0$ (Fig. 2); the dilatons tends to stop (Fig. 3), as the background converges towards the radiation-dominated, frozen-dilaton asymptotic solution; the frozen spatial dimensions start to expand ($H_1, H_2 \neq 0$), and the expansion tends to become isotropic (Fig. 4), asymptotically approaching a state in which $H_1 = H_2 = H_3$, and in which the expansion rates along the three spatial directions are all positive and decreasing.

This example is not completely realistic, for various reasons (for instance, an appropriate non-perturbative dilaton potential is expected to be included, in the post-big bang phase, to give a mass to the dilaton, and to fix the final string coupling to a realistic value [25] $\langle g_s^2 \rangle = \langle e^{\phi} \rangle \sim 10^{-2} - 10^{-4}$). Already from this simple example we can learn, however, that the back reaction of the produced radiation is possibly a key missing ingredient in previous studies of the graceful exit problem. It is a physical effect, not a term added "ad hoc" to the action, which could represent the last step of a a complete transition from the string perturbative vacuum to the present cosmological state. When such a back reaction is included, in particular, it seems possible to have a look at the pre-big bang Universe even following the geodesics of the low-energy string effective action.

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REFERENCES

[1] S. Weinberg, *Gravitation and cosmology* (Wiley, New York, 1972); E. W. Kolb and M. S. Turner, *The Early Universe*, (Addison Wesley, Redwood City, Ca, 1990).

[2] A. Vilenkin, Phys. Rev. D **30**, 509 (1984); A. D. Linde, Sov. Phys. JEPT **60**, 211 (1984); Y. Zel'dovich and A. A. Starobinski, Sov. Astron. Lett. **10**, 135 (1984); V. A. Rubakov, Phys. Lett. B **148**, 280 (1984).

[3] J. B. Hartle and S. W. Hawking, Phys. Rev. D **28**, 2960 (1983); S. W. Hawking, Nucl. Phys. B **239**, 257 (1984); S. W. Hawking and D. N. Page, Nucl. Phys. B **264**, 185 (1986).

[4] A. Guth, Phys. Rev. D **23**, 347 (1981).

[5] A. Vilenkin, Phys. Rev. D **46**, 2355 (1992); A. Borde, A. Vilenkin, Phys. Rev. Lett. **72**, 3305 (1994).

[6] A. Guth, *The inflationary Universe*, (Vintage, London, 1998).

[7] M. B. Green, J. Schwartz and E. Witten, *Superstring theory*, (Cambridge U. Press, Cambridge, Ma, 1987).

[8] G. Veneziano, Phys. Lett. B **265**, 287 (1991); M. Gasperini and G. Veneziano, Astropart. Phys. **1**, 317 (1993); Mod. Phys. Lett. A **8**, 3701 (1993); Phys. Rev. D **50**, 2519 (1994). An updated collections of papers on the pre-big bang scenario is available at `http://www.to.infn.it/~gasperin`.

[9] M. Gasperini and M. Giovannini, Phys. Lett. B **282**, 36 (1992); Phys. Rev. D **47**, 1519 (1993); R. Brustein, M. Gasperini, M. Giovannini and G. Veneziano, Phys. Lett. B **361**, 45 (1995).

[10] E. J. Copeland, R. Easther and D. Wands, Phys. Rev. D **56**, 874 (1997); R. Durrer, M . Gasperini, M. Sakellariadou and G. Veneziano, Phys. Lett. B **436**, 66 (1998); Phys. Rev. D **59**, 043511 (1999); M. Gasperini and G. Veneziano, Phys. Rev. D **59**, 043503 (1999).

[11] M. Gasperini, M. Giovannini and G. Veneziano, Phys. Rev. Lett. **75**, 3796 (1995).

[12] R. Brustein and G. Veneziano, Phys. Lett. B **329**, 429 (1994); N. Kaloper, R. Madden

and K. A. Olive, Nucl. Phys. B **452**, 677 (1995); R. Easther, K. Maeda and D. Wands, Phys. Rev. D **53**, 4247 (1996).

[13] I. Antoniadis, J. Rizos and K. Tamvakis, Nucl. Phys. B **415**, 497 (1994); S. J. Rey, Phys. Rev. Lett. **77**, 1929 (1996); M. Gasperini and G. Veneziano, Phys. Lett. B **387**, 715 (1996); S. Foffa, M. Maggiore and R. Sturani, *Loop corrections and graceful exit in string cosmology*, IFUP-TH 8/99 (February 1999).

[14] M. Gasperini, M. Maggiore and G. Veneziano, Nucl. Phys. B **494**, 315 (1997); M. Maggiore, Nucl. Phys. B **525**, 413 (1998); R. Brandenberger, R. Easther and J. Maia, JHEP **9808**, 007 (1998).

[15] Second paper in Ref. [8].

[16] M. Gasperini, J. Maharana and G. Veneziano, Nucl. Phys. B **472**, 349 (1996).

[17] R. Brustein and R. Madden, Phys. Lett. B. **410**, 110 (1997); Phys. Rev. D **57**, 712 (1998).

[18] M. Gasperini, J. Maharana and G. Veneziano, Phys. Lett. B **272**, 277 (1991).

[19] M. Gasperini, in *String gravity and physics at the Planck energy scale*, edited by N. Sánchez and A. Zichichi (Kluwer A. P. , Dordrecht, 1996), p. 305.

[20] J. B. Zeldovich and I. D. Novikov, *Relativistic Astrophysics*, (Chicago University Press, Chicago, 1983).

[21] Third paper in Ref. [8].

[22] T. Banks, W. Fischler and L. Motl, *Dualities versus singularities*, hep-th/9811194.

[23] R. M. Wald, *General relativity*, (Chicago University Press, Chicago, 1984).

[24] R. L. Abramo, R. H. Brandenberger and V. F. Mukhanov, Phys. Rev. D **56**, 3248 (1997).

[25] V. Kaplunovsky, Phys. Rev. Lett. **55**, 1036 (1985).